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# Ultralight Weight Piezoresistive Spongy Graphene Sensors for Human Gait Monitoring Applications

Debarun Sengupta, *Member, IEEE*, Ajay Giri Prakash Kottapalli\*

**Abstract**— This work reports a facile method of fabricating ultralight weight (density of  $0.305 \text{ g/cm}^3$ ) and squeezable microporous graphene-PDMS piezoresistive sensors for human gait monitoring applications. The sensor reported in this work demonstrates piezoresistivity by utilizing the conductive domain discontinuity mechanism demonstrated by multilayer graphene nanoflakes populating the inner pore walls of microporous PDMS sponges. Quasi-static compressive strain characterization experiments conducted on the sensor revealed a linear response with a gauge factor of 8.77 for compressive strains up to 9.5%. Two identical graphene-PDMS sponge sensors embedded into a pair of soft shoe-soles were used to demonstrate comprehensive real-time gait monitoring, which includes pressure profiling of the heels of both the legs.

## I. INTRODUCTION

Flexible piezoresistive sensors employing nanomaterial-polymer composites are relatively novel, and only a few researches have reported employing graphene as a sensing material for developing wearable and squeezable sensors [1]–[5]. Most of the works reported in the literature have mainly focused on the synthesis of nanomaterials with piezoresistive sensing properties. Furthermore, the limited squeezability of the devices reported in literature (owing to their two dimensional structure), poses constraints in placing the sensors under the foot for pressure profiling thus limiting the usability of such devices for practical gait tracking applications involving potential fall detection, and differentiation between feet anatomies [6].

Neurological ailments like Parkinson's disease, Huntington's disease, multiple sclerosis, and other similar conditions cause gait abnormalities in the patients and subsequently impair their functional abilities. Continuous gait data acquisition and monitoring in patients suffering from the aforementioned conditions can facilitate early diagnosis, thus enabling the healthcare professionals to design tailored treatment plans and track the progression of the diseases [7]. Practical and non-invasive human gait monitoring necessitates the availability of squeezable, and durable sensors which can be integrated into wearable shoe-soles for real-time gait data acquisition.

In this work, ultralightweight graphene-polydimethylsiloxane (PDMS) sponge sensors were fabricated by dip-coating PDMS sponges in multilayer graphene suspension solution. In our previous work, quasi-static compressive strain sensing calibration experiments were conducted on the sensors which revealed a gauge factor of 8.77 for compressive

strains up to 9.5% [1]. Morphological characterization studies were conducted on the graphene-PDMS sponges to understand their compression-induced resistance modulation property. Accelerated lifetime characterization experiments were performed on the spongy graphene sensor through cyclic compression involving 200 cycles to demonstrate its overall durability. Finally, a sophisticated gait monitoring system comprising of two identical spongy graphene-PDMS piezoresistive sensors working in parallel was used for obtaining the dynamic pressure characteristics of the two heels of an individual, thus allowing for an accurate real-time monitoring of the gait behavior.

## II. MATERIALS AND METHODS

### A. Fabrication of spongy graphene sensors

A method for developing a squeezable three-dimensional graphene-polydimethylsiloxane (PDMS) sponge-based piezoresistive sensor was realized by infusing multi-layered graphene nanoparticles into a sugar scaffolded porous PDMS sponge structure. Fig. 1 (a) shows schematic representation of the process steps involved in the fabrication of the graphene-PDMS sponges. More details of the fabrication can be found in [1], [8]. Thin multi strand electrical wires were attached to the two ends of a graphene-PDMS sponge by employing Epotek H20E conductive epoxy (Fig. 1 (b)). The multi strand wires were used for connecting the sensor to appropriate setups for sensing and characterization experiments.

### B. Circuit setup for data acquisition

For the experiments involving gait monitoring, two identical graphene-PDMS sponge sensors having resistance of approximately  $30 \text{ k}\Omega$  were chosen. The Wheatstone bridge circuit was designed appropriately with the two fixed resistors having resistances of  $33 \text{ k}\Omega$ . A  $0 - 47 \text{ k}\Omega$  variable resistor was employed for balancing the circuit creating a zero output in unloaded condition. The unamplified output from the Wheatstone bridge circuit was fed to a National Instruments data acquisition system (DAQ, NI USB-6009) for logging the sensor data continuously using National Instruments Signal Express software.

## III. RESULTS AND DISCUSSION

### A. Morphological characterization

The morphologies of the graphene-PDMS sponges were studied employing a scanning electron microscope (SEM, JSM 6360A Jeol, Japan) to understand the strain-induced resistance modulation phenomenon. Fig. 2 (a) and (b) compare the micrographs of the unloaded PDMS sponge with the graphene loaded PDMS sponge, respectively. Graphene

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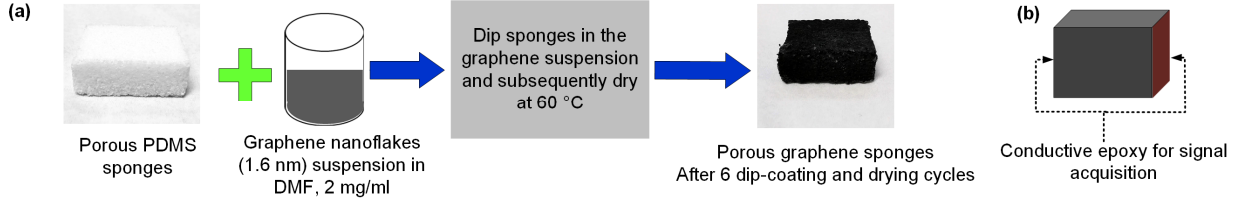


Fig. 1: (a) Process flow in the fabrication of graphene-PDMS squeezable sensor; (b) Single graphene-PDMS sponge sensor with electrical contacts.

nanoflakes were observed to have attached to the inner pore walls of the porous PDMS structure, forming a nanoflake percolation network. Fig. 2 (c) shows the schematic representation of the possible mechanism behind strain/pressure-induced resistance modulation. Any external stress/pressure would cause the graphene nanoflakes attached to the inner pore walls of the spongy PDMS to slide against each other, subsequently leading to a change in overlap area which is manifested as an overall change in the resistance of graphene-PDMS sponge.

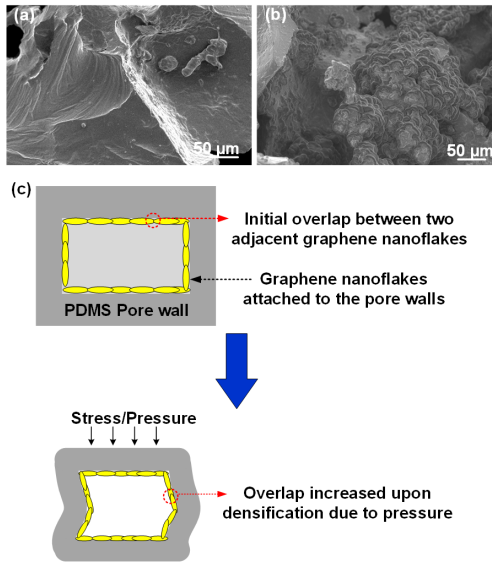


Fig. 2: (a) SEM image of the micro-porous PDMS sponge; (b) SEM image of the graphene loaded microporous PDMS sponge sensor; (c) Schematics explaining the piezoresistive sensing mechanism in the sensor.

### B. Strain sensor characterization

In our previous work, the graphene-PDMS sponge sensor was characterized for compressive gauge factor and the sensor was found to have a linear strain versus resistance change response with a gauge factor of 8.77 for strains up to 9.5% [1]. To demonstrate the response of the sensor to quasi-static compressions, the sensor was secured between two pistons (also doubling as electrodes for electrical contacts) of Instron 5940 Universal Testing Systems piezotester. Fig. 3 (a) shows the schematic of the experimental setup involving the piezotester. The piezotester was programmed to move down the top piston in steps of 50 µm to achieve a total downwards displacement of 1 mm, subsequently compressing the sponge.

The voltage response of the sensor was simultaneously acquired from the accompanying Wheatstone bridge circuit. The voltage response of the sensor was compared with the applied compression as shown by the plot in Fig. 3 (b). As observed from the plot, no noticeable delay was observed between the compression stimuli and the sensor response. The reliability of the sensor was studied by subjecting it to a series of cyclic compression-relaxation tests by developing a suitable program for the piezotester setup. The sensor was secured on the fixed bottom electrode and the movable piston of the setup was programmed to move cyclically between 0-0.3 mm, 0-0.6 mm, and 0-1 mm respectively for 80, 100 and 120 cycles respectively. Like the previous case, data was acquired continuously by connecting the sensor to a Wheatstone bridge circuit (the output of which was fed to the same data acquisition setup described previously). The plots in Fig. 4 (a - c) show the normalized resistance change response acquired from the reliability tests. Zoomed in plots placed below each of the individual corresponding main plots show the consistency of the sensor response cycles for all the applied compressive strains.

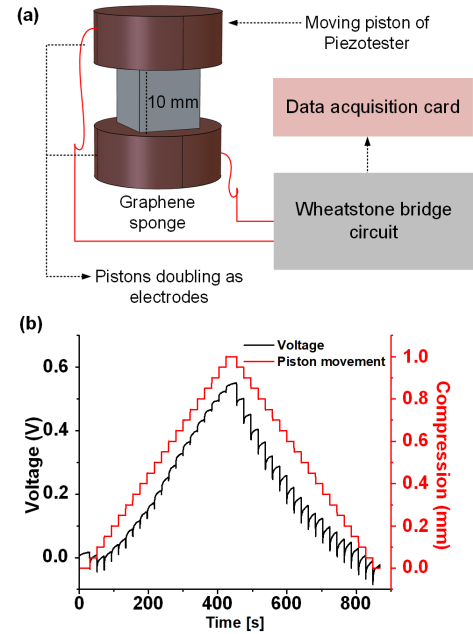


Fig. 3: (a) Schematic diagram of the experimental setup employed for piezoresistivity characterization experiment; (b) Plot showing the compressive load curve in terms of extension of the moving piston being compared with the sensor response.

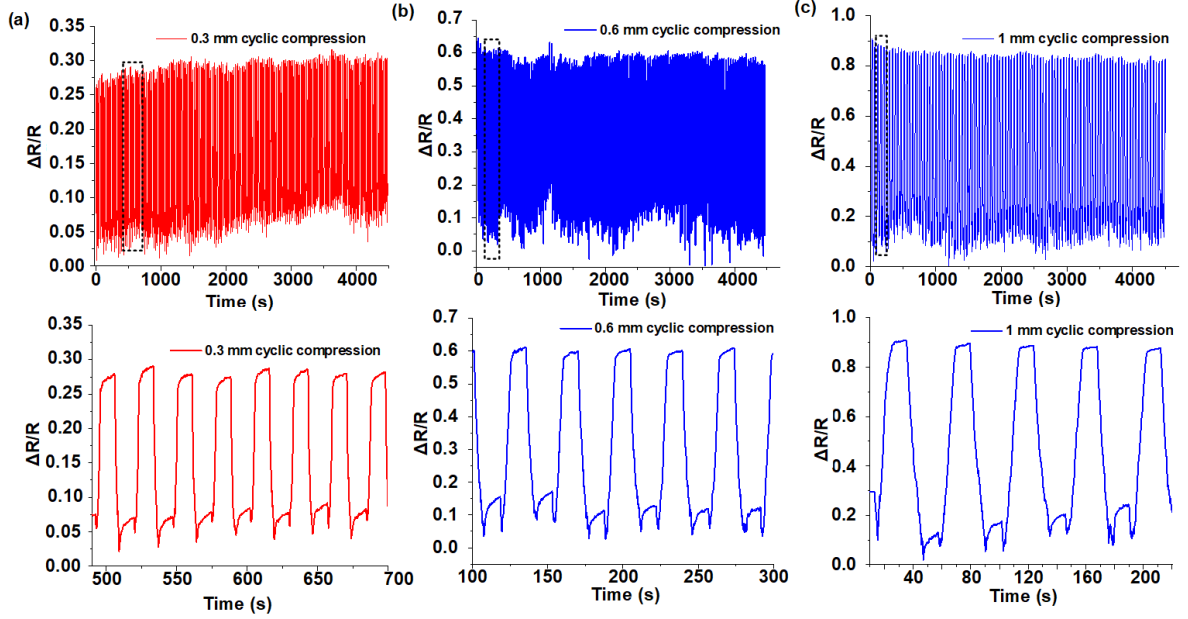


Fig. 4: Plot showing the sensor response to cyclic loading and unloading (a) at 0.3 mm compression. A zoom-in of the plot at time period 500-700 seconds shown below; (b) at 0.6 mm compression. A zoom-in of the plot at time period 100-300 seconds shown below; (c) at 1 mm compression. A zoom-in of the plot at time period 0-240 seconds shown below.

### C. Gait monitoring

To demonstrate the feasibility of using the graphene-PDMS sponges in real-time gait monitoring applications, two identical sensors having resistance of approximately 30 k $\Omega$  were secured on the heel region of a pair of soft insoles as represented by the schematic in Fig. 5 (a). The sensors were connected to appropriate Wheatstone bridge circuits described previously (Fig. 5 (b)).

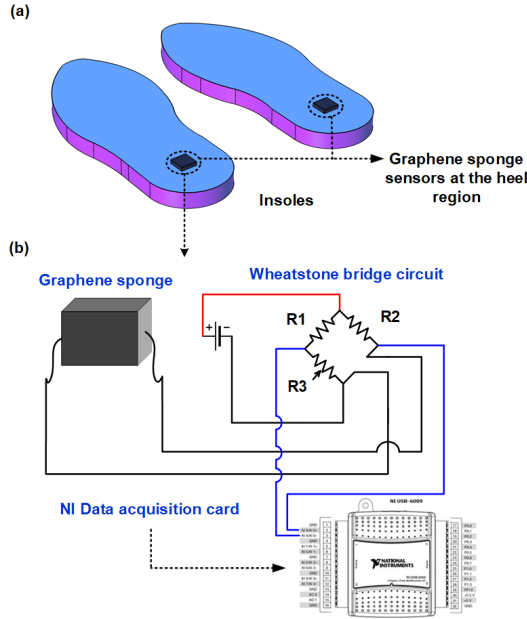


Fig. 5: (a) Schematic representation of the smart shoe sole pair for gait monitoring; (b) Schematic representation of the Wheatstone bridge circuit setup for sensor response acquisition.

The insoles were placed in a pair of sport shoes and walking/spot jogging were performed while the data was logged continuously. For both the experiments involving

walking and spot jogging, the test subject was asked to seat for 10 seconds before standing up for 10 seconds, followed by walking/jogging for 25 seconds, standing for 10 seconds, and finally sitting down. The plot in Fig. 6 (a) shows the real-time sensor responses acquired while the test subject walked at a consistent pace. The zoomed-in plot in Fig. 6 (b) shows the individual sensor responses from the two feet during the time interval 34 - 36 seconds. From the zoomed-in plot, the expected phase lag between the left and right foot while walking is evident.

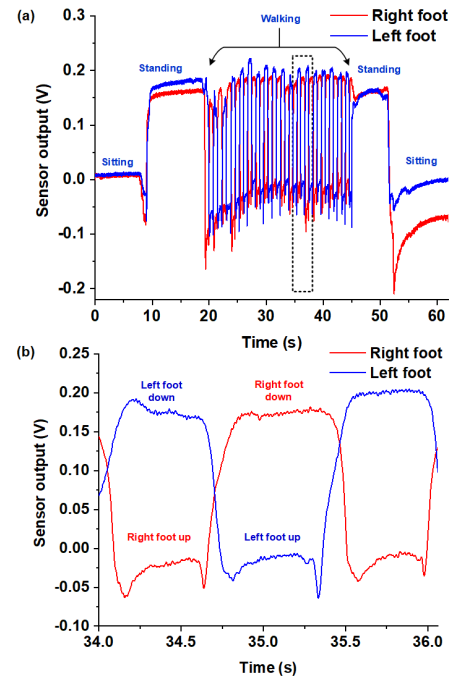


Fig. 6: (a) Plot showing the responses of the sensors from heel regions while walking; (b) A zoom-in of the plot at time period 34-36 seconds shown on the right.



The plot in Fig. 7 (a) shows the real-time sensor responses while spot jogging. The zoomed-in plot in Fig. 7 (b) shows the individual sensor responses during the time interval 35 – 37 seconds. Similar to the previous responses involving walking, the phase lag between the two feet is evident. However, the responses demonstrate sharper peaks in comparison to walking. The real-time tests involving walking and spot-jogging demonstrates the applicability of the sensor in characterizing gait and movement pattern in human subjects.

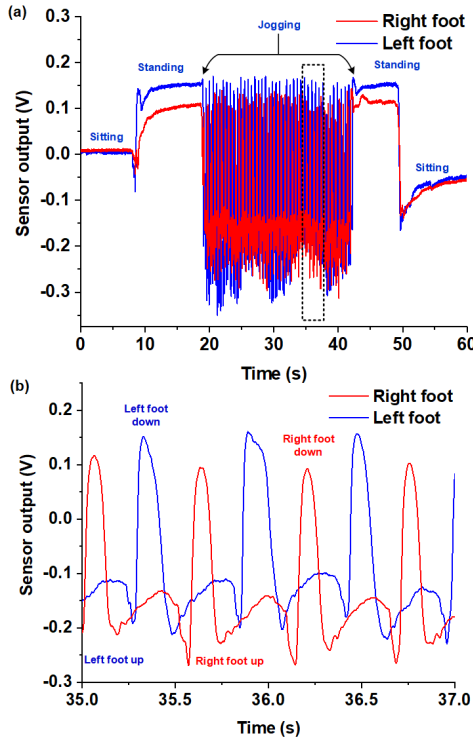


Fig. 7: (a) Plot showing the responses of the sensors from heel regions while jogging; (b) A zoom-in of the plot at time period 35-37 seconds shown on the right.

#### IV. CONCLUSION

In summary, this work demonstrated the feasibility of using graphene-PDMS sponges for real-time gait monitoring applications. Morphological studies were conducted on the

sensing elements to understand the stress/pressure-induced resistance modulation mechanisms. Quasi-static compression tests were conducted on the sensors to demonstrate their suitability for applications involving large compression/deformation. Finally, two identical sensing elements were integrated into a pair of insoles to demonstrate the potential for using the sensors in real-time gait monitoring applications.

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